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California Institute Of Technology

Keck Interferometer
Science Requirements Document

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Prepared by:

Gerard van Belle[†]
Keck Interferometer Technical Staff

Prepared by:

Gautam Vasisht[†]
Keck Interferometer Technical Staff

Approved by:

Michael Shao
Keck Interferometer Project Scientist

Concur:

Firouz Naderi
Program Manager, Origins and Fundamental Physics

Concur:

Paul N. Swanson
Keck Interferometer Project Manager

[†] The Jet Propulsion Laboratory, 4800 Oak Grove Dr., MS 306-388, Pasadena, CA 91109
Send questions and comments to G. van Belle, email: gerard@huey.jpl.nasa.gov

I. Introduction

NASA has recently established the Origins program within its Office of Space Science. The goals of this program are to search for and detect planetary systems around other stars, and to make a concerted scientific inquiry into the origins of planetary systems, stars and stellar systems, galaxies and galaxy clusters. Of ultimate interest to this program is the detection of Earth-like planets, preferably in the so-called habitable zone, and the subsequent study of their atmospheric composition.

To further the Origins program in a cost-effective and timely manner from the ground, NASA, in association with California Association for Research in Astronomy (CARA), is building the Keck Interferometer. The project will link together the two 10 m telescopes of CARA's Keck Observatory, and augment the two large telescopes with four smaller (2 m class) outrigger telescopes to create a precision astrometric and imaging instrument. By utilizing the two largest ground-based apertures available for interferometry, the Keck Interferometer will provide unprecedented sensitivity for high resolution imaging and astrometry.

The goals for the Keck Interferometer in support of the Origins program can be summarized in terms of four primary scientific objectives:

- Detect the thermal dust emission from the zodiacal dust clouds around other stars to a level equal to ten times that of our own solar system emission.
- Detect the astrometric signature of planets as small as Uranus (10 M^{-}) orbiting stars as distant as 25 pc.
- Detect the light from and characterize the atmospheres from hot, Jupiter mass planets located within 0.15 AU of their parent stars out to a distance of 15 pc.
- Make images of proto-stellar disks and stellar debris disks with ~5 milliarcsecond spatial resolution in the near- and mid-infrared.

In addition to the above goals, the Keck interferometer will open a new era in high spatial resolution imaging. As secondary science goals, there are strong scientific reasons to make the interferometer capable of observations in the following areas:

- Provide limited high spatial resolution information of faint, extra-galactic objects.
- Make high resolution observations of objects within the Solar System including asteroids, comets and distant outer planets.

From a technological standpoint, the Keck Interferometer is a proving ground for interferometric technologies that will be relevant to the Space Interferometry Mission (SIM) and the Terrestrial Planet Finder (TPF). When appropriate and cost-effective, the Keck Interferometer will incorporate hardware, software, and analysis tools relevant to these future missions.

II. System Requirements

The following specifications have been derived from the science goals for the Keck Interferometer (KI), the section number in parenthesis indicate the particular science that drives the requirement:

i. *Detection of Zodiacal Shells* - Detection of zodiacal clouds about stars 10 pc distant, at 10 µm and at 10x the solar system equivalent. (§1)
ii. *Astrometry* - The astrometric accuracy of the outrigger telescopes will have a requirement of 25 microarcseconds (µas) in one hour for sources with appropriate reference stars, with a goal of 10 µas. (§2.1)
iii. *Multiwavelength Phase Referenced Interferometery* - The interferometer will provide simultaneous

Table 1. Summary of Science Goals and Keck Interferometer Configurations		
Science Goal	Interferometer Configuration	Instrumentation
1. Zodiacal Disks	2 Keck 10-m telescopes	10 μm nulling, adaptive optics
2. Astrometric Search for Uranus-mass Planets	4 Outrigger telescopes (d>1.8 m) with two 100 m orthogonal baselines	2 μm dual star narrow-angle astrometry
3. Hot Jupiters	2 Keck 10-m telescopes	2-10 μm spectroscopy
4. Image Protostellar Disks	1 or 2 Keck 10-m telescopes plus 4 outriggers	2-10 μm broad band imaging and 2-10 μm spectroscopy
5. Faint Object Imaging	1 or 2 Keck 10-m telescopes plus 4 outriggers	
6. Imaging of Solar System Objects	1 or 2 Keck 10-m telescopes plus 4 outriggers	

multi-wavelength phase measurements to an accuracy of 10^{-3} rad for detection of color-dependent centroid shifts attributable to stellar companions. (§2.2)

iv. *Imaging* - The interferometer will have imaging spatial resolution (λ/D) ranging from 3.3 - 20 milliarcseconds (mas) in the wavelength range from 1.6 - 10 µm. *(u,v)* coverage will be set partially by site & logistical constraints. The goal is to provide a range of baseline spacings from not more than 30m to at least 85m, in orthogonal directions. (§3, §4, §7, §8)

v. *Sensitivity : Cophasing Source* - Single aperture phasing (adaptive optics) and interferometric cophasing will require at least one bright stellar source – either a separate reference star or the science target itself. The minimum K band magnitude requirements on the cophasing source are listed in Table 2.

Table 2. Performance Requirements as Derived from Science Objectives *(Actual expected performance values may be found in the appendix)*		
Aperture Pairs	Cophasing Source: m_K Limit	
	Single Baseline Cophasing	Full Array Cophasing
10 m - 10 m	15.0 (§8.3)	
10 m – 1.8 m		13.0 (§8.4)
1.8 m – 1.8 m	10.0 (§2.1)	10.0 (§2.2,§8.4)

vi. *Sensitivity : Science Source and Astrometric Reference* – With the interferometer a dim science source within one isoplanatic patch may be integrated upon for many hundreds of seconds. For astrometry, the situation is quite similar, except that the science target will always be a bright, nearby star, and the astrometric reference star will be a dim background star. The minimum K band magnitude requirement on the science/astrometric source are listed in Table 3.

vii. *Throughput* – The above science limiting magnitudes shall be met with a signal-to-noise (SNR) of 10 in 1000^s of integration time; the astrometric limiting magnitude shall be met with a SNR of 100 in 3600^s of integration time (§2.1). A definition of SNR for the instrument may be found in the appendix.

viii. *Spectral Resolution* – Comprehensive investigations into the physics of the observed objects will be greatly enhanced if wavelength-dependent information can be obtained. Source spectral information shall be recoverable with a resolution of at least R~300 in each of the bandpasses from 1.6μm to 10μm (§2.2, §3.3, §8.1).

Table 3. Performance Requirements as Derived from Science Objectives
(Actual expected performance values may be found in the appendix)

Aperture Pairs	Science/Astrometric Target: m_K Limit		
	Point Target, Simultaneous Baselines	Diffuse Imaging Target, Simultaneous Baselines	Astrometric Reference, Single Baseline
10 m - 10 m	22.0 (§8.3)		N/A
10 m – 1.8 m	17.0 (§6.0)	14.0 (§8.1)	N/A
1.8 m – 1.8 m		11.0 (§3.3)	17.0 (§2.1)

III. Origins Specific Science

1.0 Detection of Zodiacal Clouds around Other Stars

The Keck Interferometer, operating as a nulling interferometer, will be able to detect the 10 μm exo-zodiacal emission from stars 10 pc away; it should accomplish this to levels 10 times the solar system emission. A disk around a solar-type star 10 pc away, with 100 times the surface density of the dust in our Solar System, emits at ~15 mJy at 10 μm. Such a cloud is measurable with a signal-to-noise ratio of 100 in a matter of hours. Purely based on photon statistics, disks with as little material as in our system would be detectable with the Keck Interferometer; however, this will be a difficult experiment.

Known Targets: The 1,000+ targets within 20 pc as found in Gliese (1991) (see §2) constitute the set of targets for this line of inquiry.

Requirement: Detection of zodiacal clouds at 10 μm at the 10x solar system equivalent is the requirement. Derived technical requirements include a null depth of $\sim 10^{-3}$, implying good adaptive optics on both telescopes, and rapid interferometric chopping.

2.0 Planet Detection

2.1 Indirect detection of Cool Gas Giants

The outrigger telescopes of the Keck Interferometer will be explicitly designed to take full advantage of the excellent seeing at the Mauna Kea site; narrow-angle astrometry at the site should have an atmospheric limit of 10 - 20 μas in one hour. The Keck Interferometer will be able to search stars within 25 pc for the presence of planets down to 1/20 of Jupiter's mass with 10 year orbital periods (a mass roughly equivalent to that of Uranus). 25 μas accuracy is sufficient to detect such a planet in a ~10 year orbit (Jupiter-like orbital separation) around a solar-type star at a distance of 10 parsecs. A survey of stars for planets will require roughly four observations of a star per year. Assuming 10 hrs of observing a night, 50% good weather, 50% of the time the outriggers are devoted to a planet search, four observations a year, and two reference stars per observation at an hour each, roughly 100 stars may be observed annually at the highest accuracy. At lower accuracy, where the observing time per star can be reduced, the number of stars can be greatly increased (1/3 the accuracy means ~10x as many targets); another option for increased throughput with reduced accuracy would be utilizing a single reference star per target. One possible program would consist of searching 100 stars down to Uranus mass and 250 down to 5 Uranus masses, with two references for every target. For stars which indicate planetary companions, a separate program of more frequent re-observing can be conducted to further explore for systems of planets (e.g., our own sun would first indicate Jupiter, and then all of the gas giants – and the 7 orbital parameters for each - could be detected with follow-up observing.)

Known Targets: The number of available sources was calculated from those objects accessible to KI in the Gliese (1991) catalog (that is to say, bright enough at both V and K, and accessible to Mauna Kea). The goal and requirement values are established assuming a star of 1 M_{SUN} and a ~10 year orbit:

Distance Range	Potential Sources	Detection Limit: Requirement	Detection Limit: Goal
0 - 15 pc	610	1/20 $M_{JUPITER}$	1/50 $M_{JUPITER}$
15 -25 pc	1270	1/10 $M_{JUPITER}$	1/25 $M_{JUPITER}$

For a lower mass star/longer orbit, the limit of detection will be correspondingly lower; the planetary detection mass scales as $M_P \propto M_{STAR}^{2/3} P^{-2/3}$.

Requirement: The requirement for the interferometer is an astrometric accuracy of 25 µas/√hr; the goal is 10 µas/√hr accuracy. These requirements imply (due to sky coverage considerations) that KI will be able to use astrometric references brighter than m_K = 17.0. The vast majority (>98%) of stars within 25pc have m_K < 10.0; hence, KI will be able to fringe track upon stars with m_K = 10.0. Additionally, the requirement for throughput is that 350 stars can be surveyed annually for planetary companions; the goal is 500 stars or more.

2.2 Direct detection of Warm Jupiters

The Keck Interferometer will have the capability to detect Jupiter sized planets at a close separation of 0.15 AU to parent stars at a distance of 10 pc through the use of two-color phase reference interferometry. Spectral information can be used to infer details about the mass, chemical makeup, large scale cloud patterns, and rotation of these objects. Detection of these objects should be achievable in a single observation; full characterization of the orbits of these objects should be possible with observations interspersed over some small multiple of an orbital period.

Known Targets: Detection of such Jupiters should be achievable for planets at 1300 K (e.g., 51 Peg at 0.05 AU) down to 600 K (e.g., 55 Cnc at 0.11 AU) (Mayor & Queloz 1995; Marcy & Butler 1996) utilizing the 1.6 - 10 µm wavelength range available to the instrument. Currently, five candidate systems are already known to exist (51 Peg, 55 Cnc, τ Boo, υ And, ρ CrB) (Marcy 1997).

Requirements: There are over 1000 stars in the Gliese catalog (1991) with m_K < 10.0 for the KI outriggers to fringe track, which in turn shall enable the two-color phase reference interferometry from 1.6 to 10µm. Phase measurements shall be at an accuracy of 10^{-3} rad. The outrigger telescopes can survey for the hottest examples of this object class, while the Keck-Keck pair will be able to detect and conduct spectroscopy on Jupiters as cool as 600 K. Spectral of detected objects should be observable at a resolution of R~100, which is sufficient to detect methane, water and ammonia absorption bands (e.g., see the observations of GL 229B by Oppenheimer *et al*. 1995 *Sci* **270** 1478, Geballe *et al*. 1996 *ApJ* **467** 101). Higher resolution spectra at R~500 would enable even more detailed studies of brown dwarfs (e.g., see the GL 229B CO detection by Noll *et al*. 1996 *ApJ* **489** L87). As such, the requirement is for R~100, with R~500 as a goal, for the each of the interferometer wavelength bands.

3.0 Imaging

3.1 Circumstellar Disks: T Tauri Stars

Circumstellar disks are believed to be a common feature of both young and main sequence stars in various stages of development (Beckwith & Sargent 1993). These disks probably account for many of the unusual characteristics of young stars and may well play a role in early stellar evolution, the formation of binary or multiple star systems, and the formation of planets. The science of circumstellar disks may be divided into the following topics of interest: (i) mapping gas and dust morphology in disks (ii) correlations between disk properties and environmental factors such as a companion star (iii) emission lines from the various regions of the disk plane and (iv) the symbiosis between mass accretion through disks and mass outflow in collimated winds.

The most interesting properties of disks are their resemblance to nascent planetary systems. They hold the key to an understanding of our own origins and the propensity (or rarity) of planets around other stars. Disks are seen in stars from the youngest identifiable stages (Early YSO with ages $\tau < 10^5$ yr) that are definitively pre-planetary, all the way up to the main sequence when planets have presumably formed. Today, there is limited information on all these stages, especially the intermediate ones during which perhaps particles coagulate to create giant bodies.

The interferometric resolution available at 2 µm will be 4.5 mas, equivalent to a size of 0.6 AU at the distance to the nearest young stars, and close to the stellar radii of nearby main sequence stars. It is already well known that gaps develop in these disks as they evolve out to a few tenths of an AU. It is not known whether this is due to some form of dynamical clearing by planets or some other mechanism. The ability to resolve disk gaps and to understand disk structure with the resolution offered by the KI would be a marked advance in our understanding of these disks. Even at 10 µm, where most of the disk radiation is emitted, the resolution would be of order 3 AU at the distance to these stars. This will allow one to tackle the question of how disk matter is distributed during the time of formation of the giant planets. Jupiter for instance would have first cleared the primitive solar nebula to form a gap of ~1 AU at an orbital radius of 5 AU. It would obviously be possible to search for such gaps in disk brightness distributions. These will be our first attack at the theory of formation of the solar system.

Known Targets: As found in Ghez *et al.* (1993 *AJ* **106** 2005), there are 95 T Tauri stars with $m_K < 8.5$ in the two closest star forming regions accessible to the northern hemisphere, Taurus-Auriga ($\delta \approx +25°$) and Ophiuchus-Scorpius ($\delta \approx -20°$) (both at a distance of ~150 pc).

Requirement: As a requirement, the KI outriggers should be able to image the $m_K < 8.5$ objects down to a resolution of 0.6 AU (4.5 mas at 2.2 µm). Of the other ~50 known T Tauri stars in this region, the KI outriggers with one of the 10m apertures will be able to image objects of interest if the outrigger-only requirement is met. Given a desire to directly observe thermal emission of disk material, rather than merely scattered starlight, imaging at the λ/D limit must be able to be accomplished at 3, 5 and 10 µm. Spectroscopic identification of thermally emitting circumstellar material should be possible with a resolution of R~100 for each of these wavelength bands.

3.2 Circumstellar Disks: Herbig Ae/Be Stars, FU Orionis Stars

Around these more luminous stars, disk particles will be warm out to even larger distances. Particles at 1 AU or more from the central star may be imaged directly at 10 µm. Alternatively, scattered light from particles and resonant gas transitions in the disk's photosphere may allow high resolution imaging at slightly shorter wavelengths to observe more extended parts of the disk.

The advantages of interferometry will be much more pronounced for the study of the more evolved zodiacal type disks, such as the ones that are observed around β Pictoris and Vega. Currently, the images of β Pic indicate a disk structure with a density that is rising at small radii, however, it is clear from spectral energy distributions that the inner regions of the disk must be devoid of small particles. The 10 µm images of Lagage & Pantin (1994) show a marked asymmetry in the scattered light. In addition to this, a drop in intensity as one gets closer in than a radius ~20 AU to the star suggests that this is a planet or a large body which clears out an inner hole. To confirm such results and to study the way in which the dynamical gap clearing occurs, one needs the angular resolution that KI will provide.

Known Targets: As found in The *et al.* (1994 *A&AS* **104** 351), there are at least 67 'true' Herbig Ae/Be stars known to have $m_K < 9$ (cf. The *et al.*, Gezari *et al.* 1996), with many more (~200) potential protoplanetary targets listed in the same reference.

Requirement: As a requirement, the KI outriggers should be able to image the $m_K < 9$ objects down to a resolution of 4.5 mas at 2.2 μm. As in §3.1, imaging at 3, 5 and 10 μm is also a requirement, and spectroscopy at a resolution of R~100.

3.3 Astronomy in the Solar System

Planetary sources will be of interest to the Keck Interferometer. We note that no space missions to Uranus and Neptune are currently planned; KI could potentially provide a unique window into mapping the moons of the outer small bodies of the solar system. It is not clear whether "images" can be made of the lower surface brightness objects (e.g. Kuiper Belt objects) but clever visibility measurements directed at particular problems are certainly possible. Careful experiments can also be thought out for comets.

Known Targets:

i. Moons of the Gas Giants: Although the moons of the closer gas giants have been or will be explored in detail by visiting spacecraft (e.g. *Galileo* at Jupiter, and *Cassini* at Saturn), the moons of the outer gas giants Uranus and Neptune have had only cursory investigations with the flybys of *Voyager 2*. Triton, 1500 km in size and at a distance of 40 AU, would subtend an angular diameter of 50 mas; the five primary moons of Uranus would also all be in this size range. These objects would be too dim to cophase upon, but would pass periodically in front of stars bright enough for interferometric cophasing.
ii. Asteroids: As found in Veeder *et al.* (1982 *AJ* **87** 834, 1983 *AJ* **88** 1060), there are many (> dozens) objects with $m_K < 11$. A body 10 km in size at a distance of 1 AU has an angular size in excess of 13 mas, making it an ideal target for imaging with KI. In addition to imaging the primary asteroid, KI can also search for multiplicity among these objects. Astrometry of asteroid-asteroid encounters could enable mass determinations of these objects; spectrometry at a resolution of R~100 in the 1.6-10μm bands will allow for simple mineralogical mapping of their surfaces (e.g., see Lebofsky 1980 *AJ* **55** 573).
iii. Pluto: With a brightness of $m_K \approx 13$ (Soifer *et al.* 1980 *AJ* **85** 166) and an angular size of ~75 mas, Pluto is also an ideal target for imaging with KI. Currently the best images for Pluto and Charon are HST images at a resolution of ~50 mas (λ=500nm, Stern *et al.* 1997 *AJ* **113** 827); KI's limiting resolution of 4.5 mas at 2.2 μm should compliment the shorter-wavelength HST maps of the surfaces of these objects. Observations at a spectral resolution of R~300 should be able to map the surface distribution of various ices (i.e., CH_4, N_2, CO_2, etc.) (Duxbury *et al.* 1997 *Icarus* **129** 202, Gerakines *et al.* 1995 *A&A* **296** 810).

Requirement: The 10m-1.8m baselines are required to have a diffuse object limiting sensitivity of $m_K \approx 13$, with a goal of $m_K \approx 14$, and the 1.8m-1.8m baselines are required to have a diffuse object limiting sensitivity of $m_K \approx 11$. Spectral resolution of R~100 is required at the K through N bands, with a goal of R~500.

IV. Non-Origins Specific Science

In addition to achieving a number of important goals for the Origins program, the Keck interferometer offers an exciting suite of capabilities in other areas of astronomy.

Stellar Astrophysics

4.0 Imaging

KI will be able to produce images of the larger stars (40 mas, i.e. 10x10 pixels), allowing exploration of surface brightness distribution phenomena, including: stellar oblateness, limb darkening, surface features (hot and cold), extended atmospheres, wavelength dependencies of diameter. For smaller stars (4.5 - 18 mas), these phenomena also may be explored, through parametric modeling. The large aperture size of the KI outriggers and non-heterodyne nature of the instrument will allow the interferometer to observe many dim objects that are not accessible with other interferometric installations (e.g., IOTA, ISI and NPOI).

4.1 Evolved Stars: Red Giants, Supergiants, Carbon Stars and Mira Variables

KI's long wavelength capability will also allow for characterization of mass loss for these stars through observations of the dust envelopes that surround many highly evolved sources. The ability of the interferometer to track starlight tip/tilt and fringes in the infrared makes these dim, heavily reddened objects uniquely accessible to KI. Spectral information on these objects will provide insight into the atmospheric structure and evolution of these stars, and would help constrain models of stellar atmospheres.

Known Targets: From angular size estimates based upon expected stellar temperatures (Dyck *et al.* 1996 *AJ* **104** 351) and m_K values found in the Two Micron Sky Survey (Neugebauer & Leighton 1969), there are at least 15 sources that are expected to be in excess of 18 mas in size. Also in this catalog are ~230 stars in the range of 4-18 mas and ~1000 stars in the range of 1.9-4.0 mas. All of these sources are bright ($m_K < 3.0$).

Requirement: As a requirement, KI's outriggers should be able to image the surfaces of the larger ($\theta > 18$ mas) stars down to 4.5 mas resolution, partially image the stars in the 4.5-18 mas size range, and simultaneously measure the angular diameter of the stars in the 1.9-4.5 mas range with 3 separate baselines. Spectral resolution of R~50-100 should be sufficient to constrain present stellar models through observations of wavelength dependencies of angular size, limb darkening, and line absorption features (Scholz & Takeda 1987 *A&A* **186** 200, Aringer *et al.* 1997 *A&A* **323** 202).

4.2 Luminous Blue Variables, Be stars and Blue Stragglers

Binarity in massive stars is not very well studied by spectroscopy due to considerable photospheric activity in such stars (up to 30 km s^{-1}). The imaging and spectroscopic capability of KI would be an unprecedented tool in studying the structure in massive star winds (such as wind shocks) along with probing the radiative mechanism that actually drives MHD winds in such stars. Stellar exotica such as luminous blue variables (such as η Carina), Be-stars (these stars are rapidly rotating and are thought to have episodes of mass ejection in the form of equatorial disks which show considerable infrared excess) and blue stragglers in the galactic center and globular clusters (possibly products of stellar collisions) are obvious targets of interest. Better understanding of planetary formation can come from studying regions where small particles may grow, such as a dust-containing circumstellar disk where the grain-grain collision time is shorter than the disk lifetime. In addition to pre-main-sequence disks, *post*-main-sequence disks are appropriate places to investigate this phenomenon (Jura *et al.* 1997 *ApJ* **474** 741). Measuring direct masses for O and B stars and recalibration of the ML relationship for the higher mass end of the HR diagram should be feasible.

Known Targets: The 'Red Rectangle' and other post-main-sequence stars (Waters *et al.* 1993 *A&A* **269** 242). Wolf-Rayet stars, the massive progenitors of LBVs, range in size up to 72 M_{SUN} (Rauw *et al.* 1996). There are at least ~80 WR stars in van der Hucht *et al.* (1981 *SSRv* **28** 227); those with photometry listed in Gezari *et al.* (1996) are variable but tend to have $m_K < 10$.

Requirement: The KI outriggers should be able to fringe track upon and image each of these objects with $m_K < 10$.

5.0 Astrometry

5.1 Stellar masses

Detection of planetary companions and solutions to their orbits will allow for determination of stellar masses for *single* stars. All prior stellar mass determinations (aside from the sun) have been derived from binary star systems. Stellar masses will be obtained in a collateral sense from planetary detections.

Known Targets: Again, the 1,000+ targets within 20 pc as found in Gliese (1991) (see §2) constitute the set of targets for this line of inquiry.

Requirement: See §2.1 above.

5.2 Stellar Binaries: Luminosities, Distances, MLR

Binary stars play a fundamental role in observational astrophysics as they have in the past provided the only direct means for measuring stellar masses. New accurate points can be added to the empirical mass luminosity relation. In addition to dedicated investigations of these objects, many stellar binaries will be detected serendipitously from the astrometric planet search; many of these objects will be quite dim ($m_K < 17.0$), and some will be undetectable to spectroscopic investigations.

Known Targets: In the catalog of spectroscopic binaries by Batten *et al.* (1989), there are more than 1100 known targets accessible to Keck (proper dec range, $m_K < 10.0$), of which approximately 1000 have periods of less than 1 year. For these objects, less than half have *m sin(i)* listed in Batten. Additionally, it is clear from a histogram of the targets found in Batten that the catalog is incomplete past $m_K \approx 5.5$.

Requirement: In addition to the requirements in §2.1, utilizing either single-star or dual-star modes, we expect the KI outriggers to provide orbital solutions for the large majority (>95%) of the $m_K < 10.0$ objects. This requires that the outriggers will be able to fringe track upon stars with $m_K < 10.0$.

5.3 The Low End of the Initial Mass Function and Brown Dwarfs

The initial mass function of stars and sub-stellar objects is an important measurement that is only possible with high resolution imaging and accompanying spectroscopic capability. Transformation from observed luminosity functions to mass functions requires knowledge of the derivative of the M-L relationship. At present there are not enough empirical mass measurements from binaries to constrain the derivative sufficiently, while theoretical models of these extremely cool stars and massive brown dwarfs are not accurate enough to rely on. Precision radial velocity measurements have been able to detect low mass stellar and sub-stellar companions indirectly to nearby stars but an interferometer is required to obtain spectra, full orbital solutions (including masses). Masses of halo M-dwarfs would be very important because it allow us to calibrate metal poor stellar structure models that are used to determine the age of globular clusters.

Known Targets: There are at least 11 presently known brown dwarf candidates ($M < 60$ $M_{JUPITER}$) which have been detected by radial velocity means (Cochran *et al.* 1997, in press). The KI outriggers will be able to get orbital solutions for all of these objects, and search for additional candidates among the stars already being searched for planetary companions.

Requirement: In addition to the requirements in §1.2, we expect the KI outriggers to provide orbital solutions for the large majority (>95%) of these objects. This requires that the outriggers will be able to fringe track upon stars with $m_K < 10.0$. As in §2.2, compositional analysis of brown dwarfs dictates a spectral resolution of R~100 over the HKLMN bandpasses, with R~500 being a goal for the project.

Galactic Astrophysics

6.0 Astrometry

Dark Matter and Gravitational Micro-lensing

Micro-lensing offers a new technique for determining the nature of dark matter in our Galaxy. Existing micro-lensing surveys are now finding dozens of star-star lensing events in a year. Expanded surveys will yield many more such lensing events. However, existing surveys provide only photometric information about the light curve of the lensed source. The Keck Interferometer will be able to provide an astrometric position shift towards the lensed source as far out as the Galactic bulge (20 μas upwards) (Boden 1997). The measurement of the positional shift would provide unique information about the nature of the lensing potential, and assuming spherical symmetry, a unique determination of its mass. The nature of dark matter is one of the outstanding puzzles in modern astrophysics. If a large fraction of dark matter is made of MACHOs, then the arrival of large ground based interferometers would be most useful to existing (and upcoming) microlensing experiments, in tackling the mass distribution of dark matter. We note that while the light-gathering power of the Kecks would be well applied to this problem, the 10m apertures are unfortunately not optimized for astrometry and may not be able to contribute significantly to this particular opportunity.

Known Targets: The microlensing events will be too dim to directly cophase the interferometer upon; however, assuming a bright nearby source, astrometric observations of these objects may be conducted. Assuming an annual detection rate of 100 MACHO microlensing events a year (consistent with rates as found in Alcock *et al.* 1997), of which it is assumed that ~10% of these disk events can be phased upon, KI should have the potential to detect the astrometric shift for 10 MACHO events a year. 10% is greater than the expected outrigger sky coverage of 2.2% (see Appendix) but the events are expected to take place at a galactic latitude of ~0°, where there is a correspondingly greater number of cophasing sources available. For the events currently detected in the year to date, the average m_V is 19.2, indicating an expected average m_K of 16.2, well within the performance margin for the astrometric observing mode.

Requirement: The outriggers must be able to use a star as dim as $m_K \approx 16.2$ as an astrometric reference. Also, low resolution spectral dispersion (R~50) of the results will be necessary for determination of the amount of measurement bias introduced by light from the lens itself.

7.0 Imaging

The Galactic Center: The Central Tenth of a Parsec

Recent high resolution imaging studies of the Galactic center with the ESO NTT have demonstrated the presence of different stellar populations in the central cluster of the Galaxy. These studies have also allowed astronomers for the first time to derive the core-radius of the central stellar cluster and revealed for the first time an infrared counterpart to the radio position of Sgr A*, a prime candidate for a massive black-hole. In the case of the Seyfert NGC 7469 (at 66 Mpc), similar observations have revealed a powerful circumnuclear starburst ring responsible for 2/3 the bolometric luminosity of the entire galaxy. Clearly the Keck Interferometer would be boon to further such studies.

Evidence for a central massive black hole of $\sim 10^6$ solar masses has been accumulating for the past 20 years. A coherent determination of the central density and black-hole mass (most probably related to the radio source Sgr A*) requires a knowledge of the full three dimensional velocity dispersion of stars in the very central core. The Galactic center has several such stars for which proper motions are being measured using speckle interferometry on time-scales of a few years (Genzel *et al.* 1996). A full 3-dimensional velocity picture from radial velocity and proper motions with the Keck Interferometer on short time baselines (1 month) with far fainter magnitudes could be constructed to determine the nature of the central dark mass.

Requirement: KI should be able to construct image maps of the central region of the galaxy, at a resolution of approximately 40 AU (4.5 mas @ 8.5 kpc, 2.2 μm), and a limiting K magnitude of 17.0.

Extragalactic Astronomy

8.0 Imaging

8.1 The Circumnuclear Regions of AGNs and Starbursts

High spatial resolution infrared imaging with both Keck adaptive optics and interferometry will result in very significant progress in our understanding of Galactic nuclei. Obscured star clusters and bright individual stars can be studied in great detail. The distribution and dynamics of interstellar gas disks and flows on scales of a few parsecs or less can be investigated. The environments of massive central black-holes can be studied on scales of less than 10^3 Schwarzschild radii. Nuclei of spiral galaxies are often embedded in large columns of interstellar material with equivalent hydrogen columns being fifty times larger at 0.5 µm than at 5 - 10 µm.

Recent K band speckle imaging of the nucleus of the Seyfert NGC 1068 (Weinberger *et al.* 1996 *BAAS* **189** 1005) reveals a bright active nucleus at infra-red wavelengths, which has long been thought to harbor a massive black hole as the central engine. However, in order to show the infall of the matter itself, one would need a resolution of less than a light-year, and there is currently no way to make such finely detailed pictures. Kinematics of these regions with a resolution of $v\sim100$ km/s would require R~3000, which is beyond the capability of the first generation of KI instruments; however, with the planned capability of R~300, investigations into the nature of the circumnuclear regions of these galaxies will be greatly augmented (e.g., Marconi *et al.* 1996 *A&A* **315** 335).

Known Targets: In Lipovetsky *et al.*'s catalog of Seyfert galaxies (1988 *SoSAO* **55** 5), there are more than 200 objects with $m_K < 14$, representing only a subset of the total AGN targets. At a distance of 15 Mpc (Unger *et al* 1992 *MNRAS* **258** 371), the core of NGC 1068 would be resolvable down to just under a light-year with KI.

Requirement: The 10m-1.8m baselines must be able to fringe track off of a bright source with $m_K \approx 14$, and construct images from diffuse targets of a similar brightness. Spectral resolution must be at R~300 for the instrumental bandpasses.

8.2 Gravitational Lenses: Mass of the Lensing Galaxy, Hubble Constant

Images of complex objects such as these are meaningful only as a follow-up to AO observations carried out at the 50 mas resolution. However, the Keck Interferometer in principle can provide detailed structure of high-redshift lensed images such as rings, arcs and quads lenses. The detailed morphologies would assist modelers of the lensing Galaxy to make far superior models of the gravitational potential distribution of the lensing object. At present, errors to the measurement of the Hubble constant derived from time-delay measurements along different lines-of-sight to the lensed object, are dominated by uncertainty in the structure of the lensing potential.

Known Targets: As an example, Colley *et al.* (1996 *ApJ* **461** L83) use the morphology of the lensed galaxy to reconstruct the lens itself. Many of the candidates are beyond the limits of spatial resolution even for HST (Ratnatunga *et al.* 1995 *ApJ* **453** L5); however, the dimness of both the lens and the source will certainly necessitate the use of at least one of the 10m apertures if such an investigation is to be pursued.

Requirement: No requirement is associated with this potential science.

8.3 Expansion of Supernovae in Nearby Galaxies: the Extragalactic Distance Scale

The ejecta of young supernovae undergo unconstrained expansion for a few hundred years after the supernova itself. The initial expansion itself may have ejecta velocities of 5,000 - 10,000 km s^{-1}. With the Keck Interferometer, this expansion may be observed from the very initial stages, i.e., from when the shell is only 0.005 pc in diameter (assuming a distance of 0.6 Mpc) in galaxies in the Local Group. Using velocity information on the ejecta from spectroscopy, the distance to the supernova and therefore to the host galaxy is easily inferred. This technique has already been applied with success to infer the distance to the LMC (with SN 1987A) using high resolution HST data, and to M81 (SN 1993J) using radio VLBI. Radio VLBI, although successfully applied in the case of M81, is not a guaranteed technique because several supernovae do not become powerful radio emitters until much later in their dynamical expansion stage. Unfortunately, shell diameter measurements to the Virgo Cluster at 10 Mpc is not possible, due to the dimness of the source 15 yr after outburst, when the shell would be resolvable by Keck.

Known Targets: A project of this nature will require the fortuitous occurrence of a supernova in a nearby galaxy; e.g. SN 1987A could be directly cophased upon with the interferometer (peak m_K = 3.26, Bouchet & Danziger 1993 *A&A* **273** 451). The twin Kecks, however, could be utilized to make a shell diameter measurement of a much dimmer supernova. At a distance of 0.6 Mpc (roughly M31), the diameter of a shell 0.005 pc in diameter could be measured. Ten years after the 1987A explosion, the fireball was 0.05 pc in diameter (Pun & Kirshner 1996 *AAS* **189** 4504). From that, a size of 0.005 pc after one year may be inferred; at that time 1987A was $m_K \approx 9.0$, indicating $m_K \approx 14.4$ at 0.6 Mpc. Based upon expected supernovae rates (van den Bergh & Tammann 1991 *ARAA* **29** 363, which admittedly are quite uncertain), there should be an observable supernova within the Local Group once every 5 to 20 years.

Requirement: The 10m-10m baseline needs to have a on-axis source limiting sensitivity of $m_K \approx 15.0$ for direct cophasing upon supernovae out to Andromeda. Using a bright foreground star for cophasing, the 10m-10m baseline needs to have an off-axis point source limiting sensitivity of $m_K \approx 22.0$ for shell diameter measurements out past the Local Group (to ~1.8 Mpc, at 3 yr after outburst).

8.4 Spiral Galaxies: Evolution of the Spiral Structure

The Keck Interferometer should be able to resolve the disks of spiral galaxies in the very early universe. This would assist in easy identification of galaxy-types and determination of their relative number densities with z (at present this is a hard problem even for Galaxies out to a red-shift z = 1.0), which has direct bearing on any scenarios of galaxy evolution and galaxy-galaxy interaction in the cluster environment. In addition, resolving disks of spiral galaxies at large look-back times would go a long way in the understanding of formation of spiral structure in the early universe and the physics of density wave propagation.

Known Targets: Using an average B-K color of ~0.3 (from a spot check of randomly selected galaxies in Gezari *et al.* 1996), and examining the photometry in the redshift catalog of Rood (1980), we expect at least 35 spiral galaxies with $m_K < 10$, and 500 with $m_K < 13$.

Requirement: The 10m-1.8m baselines need to have on-axis source and off-axis diffuse imaging object limiting sensitivities of $m_K \approx 13$, and the 1.8m-1.8m baselines need to have a on-axis source and off-axis diffuse imaging object limiting sensitivities of $m_K \approx 10$.

V. Appendix

Definitions

Signal to Noise Ratio (SNR) – In many cases the SNR for an interferometer is ambiguously defined. In this document, we intend SNR to denote the ratio of detected fringe signal to detected noise. The fringe signal is the visibility and phase of the fringes in the case of interferometric imaging, and simply the fringe phase in the case of astrometric observing. Major noise sources considered include the atmospheric and photon noises, in addition to a variety of other expected sources, such as baseline noise, metrology noise, and differential chromatic refraction, among others.

Expected Performance Parameters

Performance parameters have been established from first principles, taking into account all expected sources of error. For details of this evaluation of the interferometer's performance, the interferometer error budgets as prepared by M. Colavita are suggested. Further notes on some of the parameters:

Sensitivity : K Band

Expected K band (2.2 μm) magnitude limits are as follows:

Aperture Pairs	On-axis Source: m_K Limit		Off-axis Source: m_K Limit		
	Single Baseline Cophasing	Full Array Cophasing	Point Target, Simultaneous Baselines	Diffuse Imaging Target	Astrometric Reference
10 m - 10 m	15.2 (39%)	14.1 (22%)	22.1	19.1	N/A
10 m – 1.8 m	12.0 (5.7%)	11.9 (5.3%)	20.1	16.5	N/A
1.8 m – 1.8 m	10.8 (2.2%)	10.0 (1.2%)	18.2	14.8	17.0

Source: M. Colavita & G. van Belle, Keck Error Budget, 9/4/97.

Notes on the above table:

1. For a bright source, the numbers in parentheses indicate sky coverage - the mean likelihood of a target brighter than m_K within 20" for any given part of the sky (see (6) below).
2. The dim source in all cases is assumed to be 20" away, with an isoplanatic patch size of 20".
3. Off-axis source limits for point and diffuse imaging target are computed using SNR=10, t=1000^s.
4. Diffuse imaging target visibility is assumed to be 100x less than the point source target visibility.
5. Off-axis astrometric limits are computed using SNR=100, t=3600^s.
6. Sky coverage was estimated by utilizing the visual star counts per square degree as found in Allen (1976) for a galactic latitude of b = 30°. Assuming a mean spectral type of K5, a mean $V - K$ color of 3 was estimated from the spectral type dependent $V - K$ values as found in Bessell & Brett (1988). The mean

V - K color was utilized in adjusting the star counts present in Allen to K band star counts, from which the probability of intercepting a star of sufficient K band brightness within 20" was computed.

Sensitivity : Other Bandpasses

Expected magnitude limits for off-axis sources for the other bandpasses are as follows:

Bandpass	4 Outriggers	1 Keck + 4 Outriggers		2 Kecks + 4 Outriggers		
	1.8m / 1.8m	*10m / 1.8m*	*1.8m / 1.8m*	*10m / 10m*	*10m / 1.8m*	*1.8m / 1.8m*
H (1.6 μm)	19.1	21.2	19.0	23.5	21.0	18.8
L (3.5 μm)	13.5	15.3	13.3	17.1	15.1	13.2
M (5 μm)	11.0	12.7	10.8	14.5	12.6	10.7
N (10 μm)	7.5	9.2	7.3	10.9	9.1	7.2

Source: M. Colavita & G. van Belle, Keck Master Sensitivity Spreadsheet, 9/4/97.

Notes on the above table:
1. The dim source in all cases is assumed to be 20" away, with an isoplanatic patch size of 20".
2. Off-axis limits are computed using SNR=10, t=1000^s.

Spectral Resolution

From the baseline design of the sixway beam combiner, we expect the H to N bandpasses to be each dispersed over a range of 64 pixels, permitting a spectral resolution of R~100-500, depending on wavelength.

Band	Effective Center Wavelength (μm)	Width (μm)	Upper (μm)	Lower (μm)	Spectral Resolution
J	1.25	0.30	1.10	1.40	N/A
H	1.65	0.30	1.49	1.78	350
K	2.20	0.34	2.03	2.37	400
K'	2.12	0.34	1.95	2.29	400
L	3.50	0.54	3.22	3.76	400
L'	3.83	0.65	3.50	4.15	375
M	4.70	0.60	4.40	5.00	500
N	11.00	6.00	8.00	14.00	115

References: Elias *et al.* (1982 *AJ* **87** 1029); Bessell & Brett (1988 *PASP* **100** 1134).

Revision History

Release 2.0, 19 Nov 1997: Added requirements for spectral coverage. Detailed requirements for long wavelength bandpasses also added. Signature page added. Comments and suggestions from C. Beichman and S. Ridgway incorporated into the text.

Release 1.4, 18 Sep 1997: Initial release. Detailed K band requirements of the interferometry, and expected astrometry program. Distributed at the 19 Sep 1997 UCLA workshop on Interferometry with the Keck Telescopes.